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Westinghouse Astronuclear Laboratory

PERFORMANCE OF JPL TUBULAR THERMOELECTRIC MODULE (TEST ASSEMBLY 909E687)

Contract CU-388002

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INTRODUCTION

This report documents test data taken on a tubular thermoelectric module produced by Westinghouse Astronuclear Laboratory for the Jet Propulsion Laboratory under Jet Propulsion Laboratory contract CU-388002. The design of the module is defined by WANL drawing 909E686G01A. It is further identified by the code TEM-8A, Serial Number 1. The details of its design and fabrication were previously described in WANL-TME-1438, Design Analysis of JPL Tubular Thermoelectric Module.

ROOM TEMPERATURE CHARACTERISTICS

After autoclaving, the end caps were removed to expose the power leads from the thermoelectric circuit, and room temperature resistance measurements were made. The resistance of the circuit was measured with a Keithley Model 503 milliohmmeter and the resistance between the circuit and clad was measured with a John Fluke Model 710A impedance bridge. Such measurements were also taken at various stages during instrumentation of the module. The results are shown in Table 1.

TABLE 1

ROOM TEMPERATURE RESISTANCE MEASUREMENTS

Measurement Made After	Circuit (ohms)	Circuit to Clad (ohms)
1) Removal of End Caps	.112	6968
2) Welding on Heater Bulb	.102	6758
3) Welding on Conductor Rings	.102	6132
4) Welding on Conductors	.125	6367
5) Welding on Thermocouple Plug	.127	6272

To determine the axial uniformity of the module, a heater traverse test was performed prior to instrumentation of the module. In this test the module is placed in a test fixture in which the outer clad is cooled with flowing water (~ 26°C) while an electric heater with a 0.5 inch heat zone is traversed through the inner clad in 0.25 inch steps. At each position, 50 watts was applied to the heater for 30 seconds and the maximum open circuit voltage was recorded. The results of this test are shown in Figure 1. The voltage drops rapidly near the ends of the active length, as expected, due to end effects. Significant variations in behavior are evident within the active length of the module. These fluctuations could be due to either intercouple shorts or variations in the thermal contacts within the region being heated, resulting in variations in the temperature drop across the thermoelectric material.

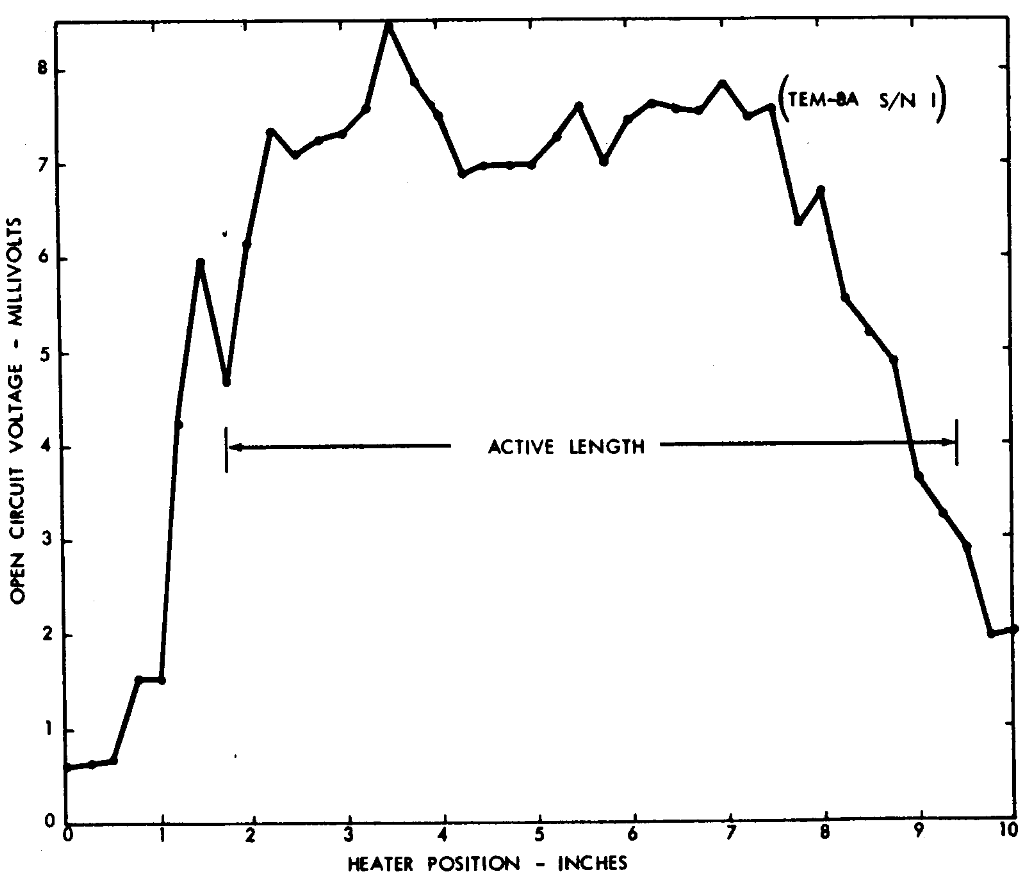

Figure 1. Results of Heater Traverse Test

ELEVATED TEMPERATURE TESTING

TEST INSTRUMENTATION

Figure 2 is a photograph of typical modules on test within the thermoelectric module static testing hood. The aluminum shroud, which surrounds the module and associated cooling fins, can readily be seen as can the inlet to the blower located below the shroud. Details within

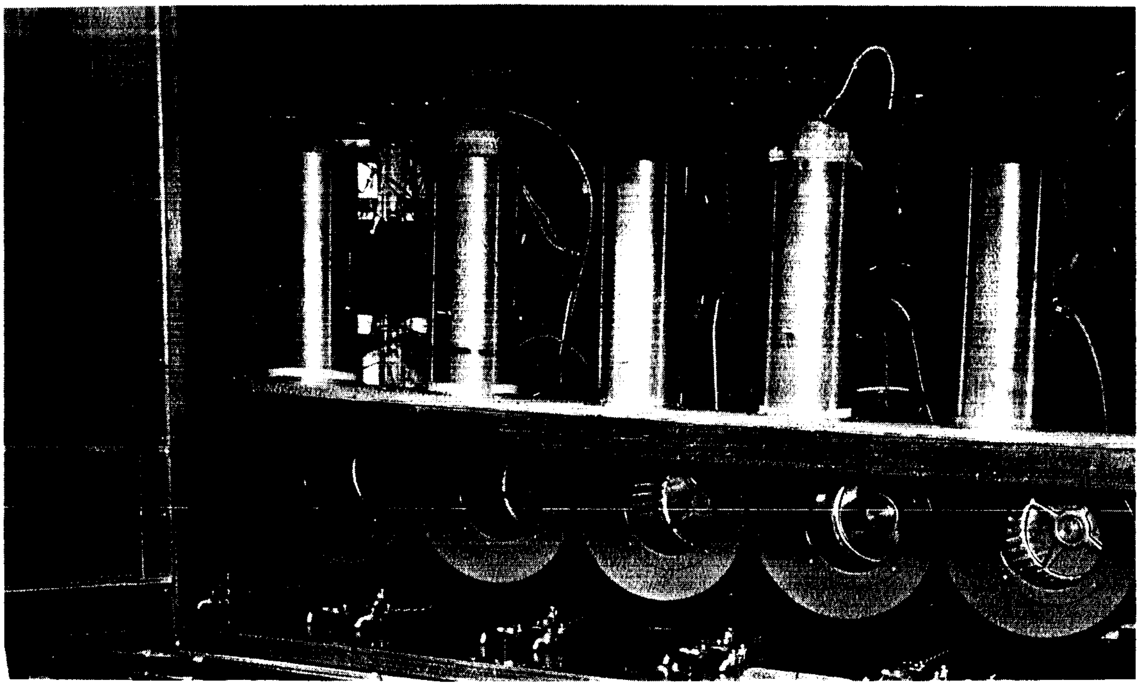

Figure 2. Photograph of Typical Modules on Test

the shroud for the TEM-8A/SN-1 modules are presented schematically in Figures 3 and 4. During testing of this module, the leads for the thermocouples and the current-voltage probes were brought out of the hood in separately shielded conduits. The thermocouples were taken to a reference junction unit in a special instrumentation cabinet. Three sets of current voltage-probes were connected directly to a terminal strip mounted on the side of the cabinet. All items of instrumentation, except the power supplies for the heaters, were packaged in a special movable instrument cabinet. Power for the instruments in this cabinet was supplied through an

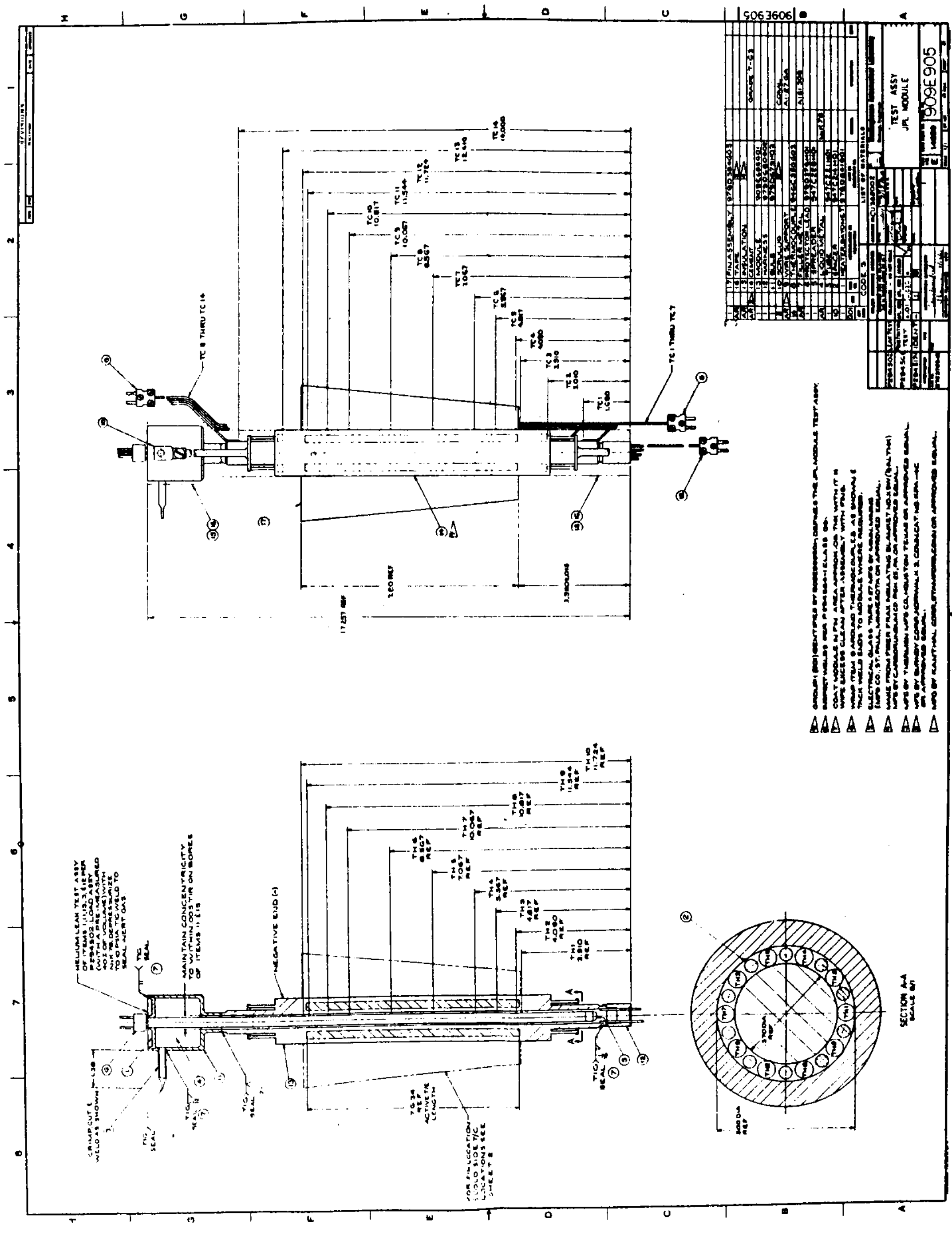

Figure 3. Details Within the Shroud for the TEM-8A/SN-1 Module

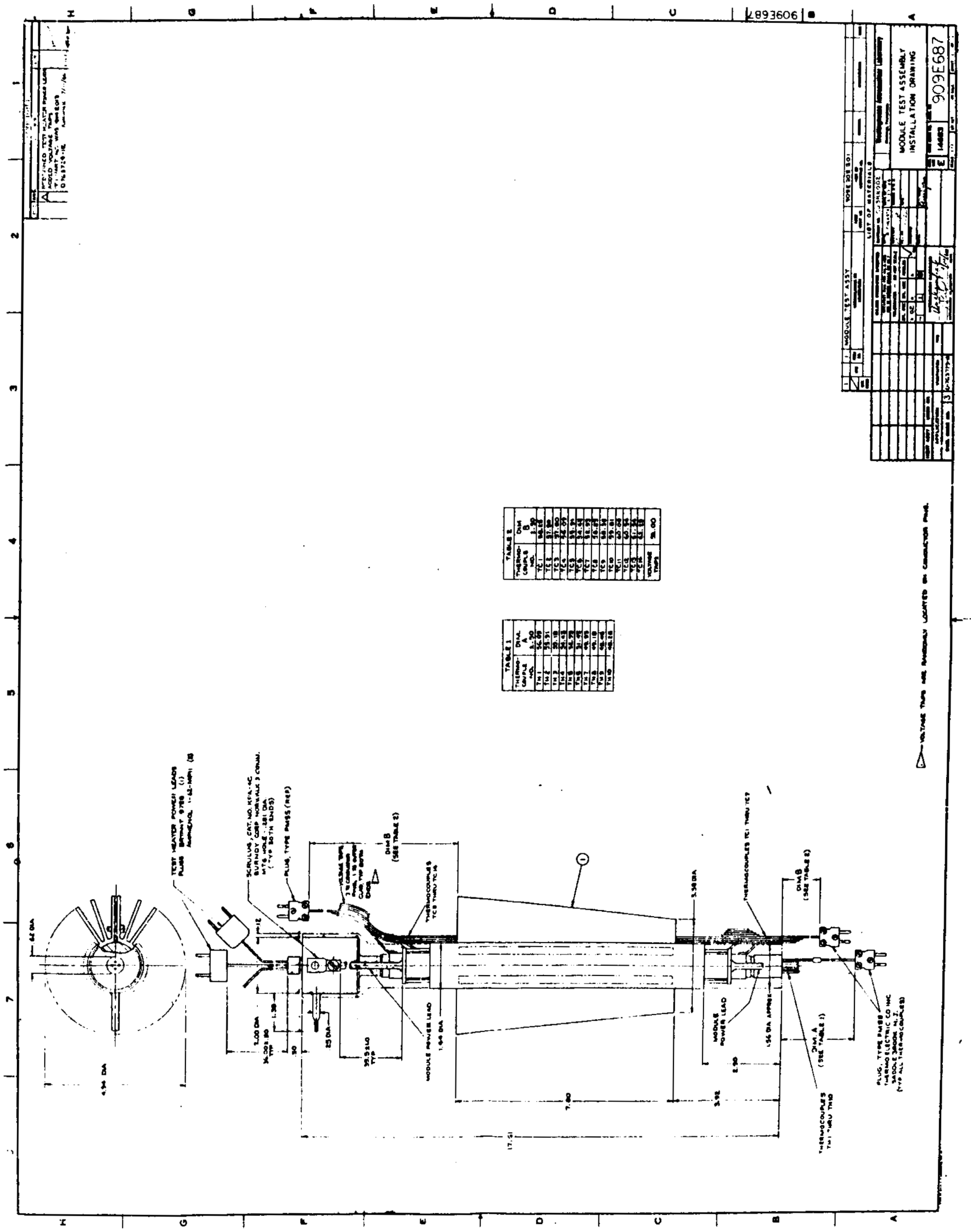

Figure 4. Details Within the Shroud for TEM-8A/SN-1 Module

isolation transformer and a constant voltage transformer. The shields on the various leads coming from the test hood were insulated from ground and from the instrumentation cabinet. The heater power supplies and associated monitoring equipment were located in a separate console which contains all the power supplies for the static test stands. The instrumentation console is shown in Figure 5. A diagram of the power supply electrical circuit for a single module is given in Figure 6. The heater power leads were also shielded and were grounded to the hood.

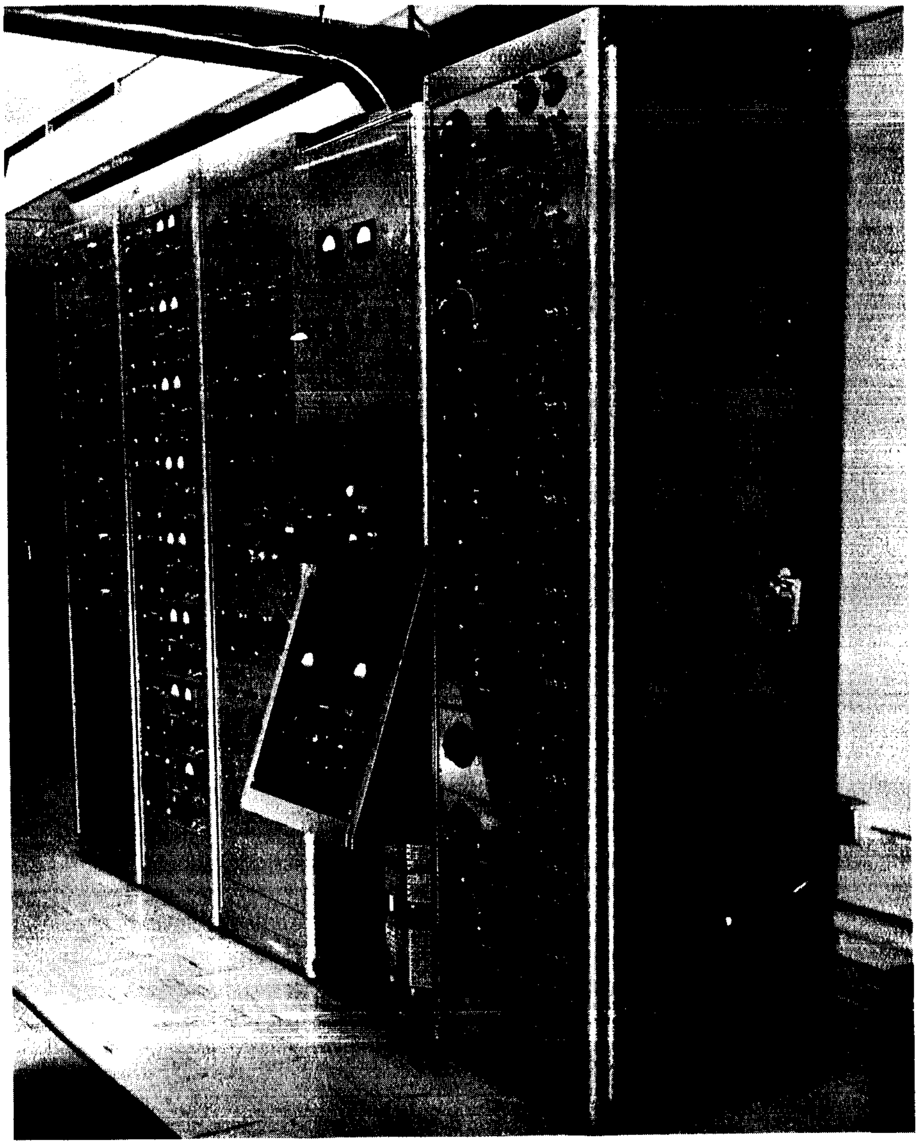

Figure 5. Instrumentation Console

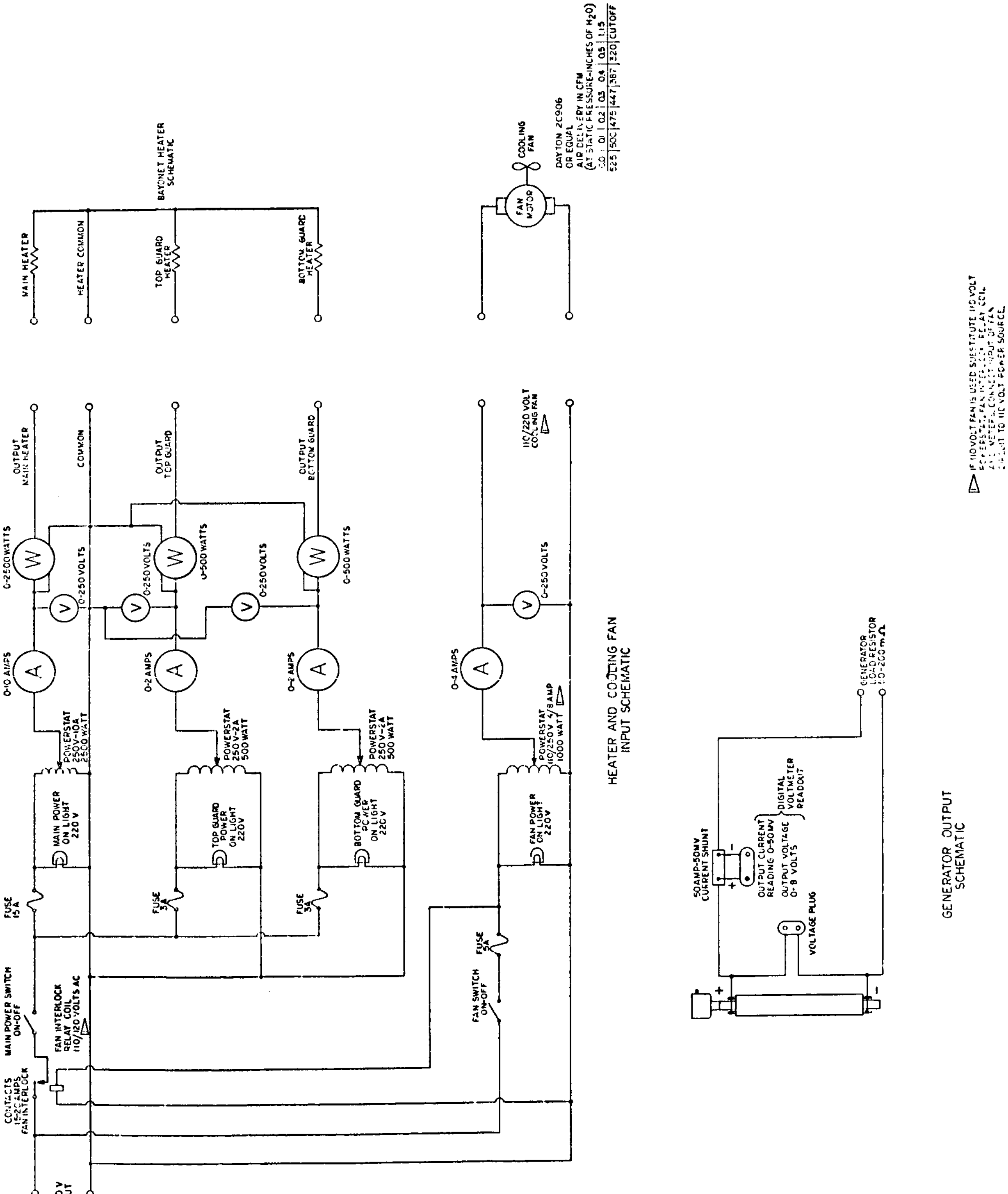

Figure 6. Schematic - Power Supply WANL Drawing 909E931

MEASUREMENT METHODS

Temperatures

As mentioned above, the thermocouple leads were led directly to a reference junction unit (Thermoelectric 50°C "Auto Ref") on the instrumentation cabinet. The outputs from this unit were connected into a 50 channel Cubic model AS-1A slave scanner. The scanner is controlled by a Cubic model MS-1A master scanner whose output is then fed to a Cubic model A-85 DC amplifier and thence to the visual readout of a Cubic model V-71P digital volt meter (DVM). Figure 7 shows a schematic of this system. Permanent record of the readouts is obtained via a Hewlett Packard printer attached to the output of the DVM.

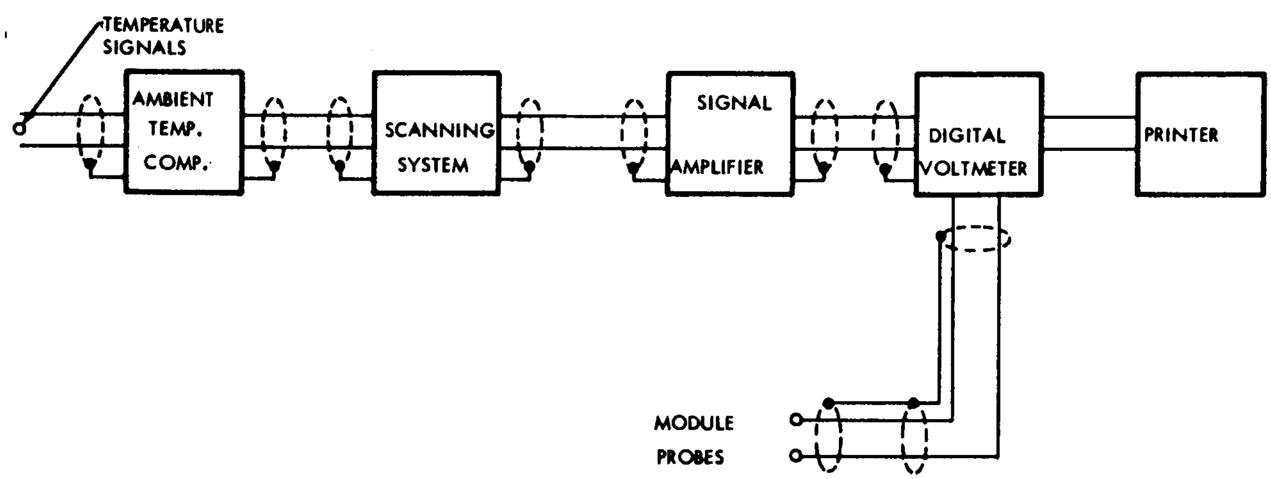

Figure 7. Block Diagram Temperature Monitoring System

Module Probes

The probes used for open circuit voltage, internal resistance, and resistance-to-clad measurements were connected directly to the input of the DVM, bypassing the DC amplifier.

Internal Resistance

The apparatus used to measure circuit resistance is shown schematically in Figure 8. Basically, a measured 60-cycle alternating current is passed through the module, and the resulting voltage drop across its terminals is measured. The circuit resistance is then established by Ohm's Law. While performing the measurement, loading of the module by the alternating current source is avoided by impressing a direct current voltage, equal in magnitude but opposite in polarity to the module voltage, in series with the module and with the alternating current source. This external direct current voltage source, when equal to the module voltage, prevents any direct current flow in the circuit.

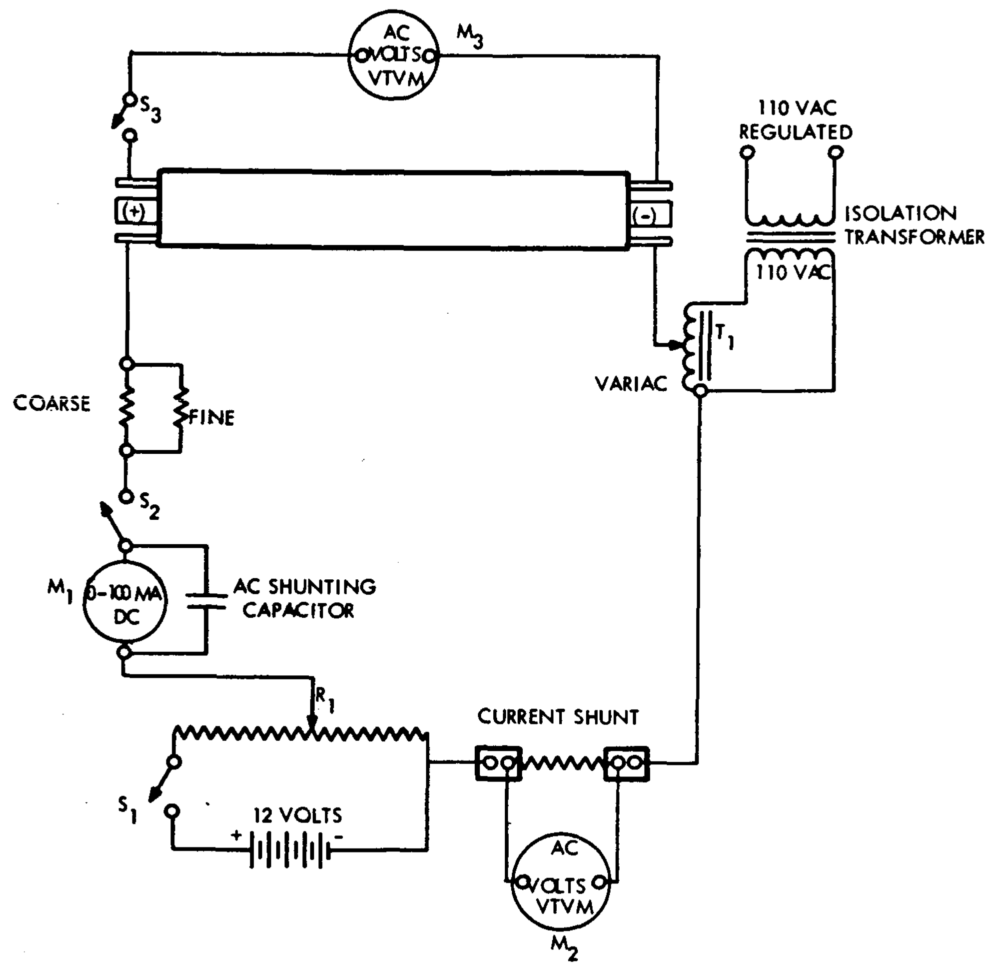

Figure 8. Schematic - Circuit for Four Probe Method of Module Internal Resistance Measurement

Resistance to Clad

The measurement problem encountered in making circuit-to-clad resistance is one of more unknowns than can be solved by measurement. A model of the thermoelectric circuit used, Figure 9a, is a series combination of ideal voltage sources (v_x) and resistances (r_x) representing the voltage across and resistance through a given single leg of a thermoelectric couple. Therefore, $R_g = r_1 + r_2 + \ldots r_n$ and $V_{oc} = v_1 + v_2 + \ldots v_n$ for an n/2 couple module.

Assuming there is a single short (R_1) at the first leg, the measurement is made across terminals A and B, and reduces to Figure 9b.

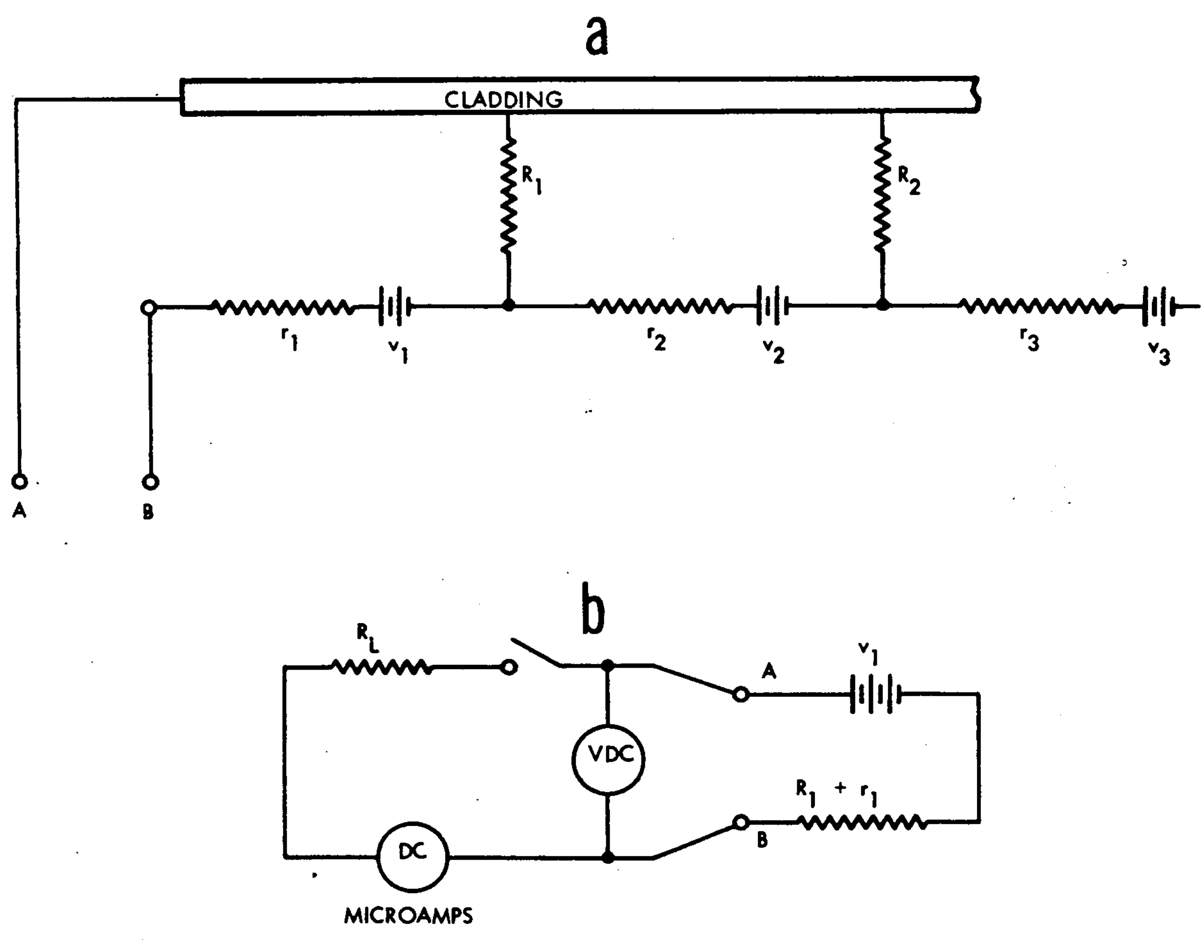

Figure 9. Schematic - Circuit for Thermoelectric Circuit-to-Clad Resistance Measurements

The resistance $R_1 + r_1$ is calculated from Ohm's Law

$$R_1 + r_1 = \frac{v_1 (oc) - v_1 (L)}{I_L}$$

where:

v_1 (oc) = voltage across A and B with no load.

v_1 (L) = voltage across A and B when loaded with the resistor R_L.

I_L = load current flowing in the circuit.

Normally, $R_1 >> r_1$ and thus $(R_1 + r_1) \simeq R_1$ which is then taken as the leakage resistance circuit to clad.

When multiple leakage paths from circuit to clad occur, the analysis is more complex, however, the same method of measurement is used and the value obtained is the effective leakage resistance of the parallel resistances from circuit to clad, R_c. This method has been used successfully when the value of R_c is less than 500, 000 ohms. For higher values of R_c, the difference between v_{oc} and v_L is not large enough to be detected. Other methods are now under investigation for measurements in the megohm range. As yet, no shorts have developed where $R_c < R_g$.

Power Output, Efficiency and Current

Using the open circuit voltage, internal resistance and average hot and cold clad temperatures measured by the above techniques, the electrical power output, P_e, the overall efficiency, η, and the current, I, of the device were then calculated for matched load conditions to within a 10 percent accuracy by:

$$P_e = \frac{V_{oc}^2}{4 R_g}$$

and

$$\eta = \frac{P_e}{Q_{in} + P_e \left[2 \frac{\bar{T}_H}{\Delta T} - \frac{1}{2} \right]}, \text{ where temperatures are degrees Kelvin}$$

$$I = \frac{P_e}{.5 V_{oc}}$$

where Q_{in} is taken as the electrical power supplied to the main heater as measured on a Westinghouse type PY-5 wattmeter, $\bar{T}_H$ is the mean hot side temperature, and ΔT, the average temperature across the module.

Parameters calculated using the above equations can differ from actual matched load values by small amounts. This is due primarily to the Peltier effect which results in smaller temperature drops across the thermoelectric materials for the loaded operation then for open circuit operation. Table 2 presents results of the theoretical calculations performed for both open circuit and matched load conditions. The average hot and cold clad temperatures, obtained from the first point at life test conditions of TEM-8A/SN-1, were used in both calculations. The calculated temperature distributions for the two cases are shown in Figure 10. As can be seen from Table 2, the differences between values in the two cases are less than 10 percent.

STARTUP

The module was placed in the static test fixture and brought slowly up to the initial test temperatures of 200°C on the cold clad and 537°C on the hot clad (average temperatures). Power was increased in small increments (50 watts/step) in order that any sudden changes in performance might be observed.

TABLE 2

SELECTED PERFORMANCE PARAMETERS CALCULATED FOR FIRST POINT AT LIFE TEST CONDITIONS

Item	Parameter	At Matched Load Conditions	At Open Circuit* Conditions	From Experimental Data*
1)	Open Circuit Voltage (volts)	5.552	5.816	5.218
2)	Current (amps)	32.41	34.01	38.94
3)	Electrical Power Output (watts)	89.96	98.91	101.60
4)	Total Thermal Power Input (watts)	1720	1817	1721
5)	Overall Efficiency	5.23	5.44	5.90
6)	Internal Resistance of Generator (ohms)	0.0856	0.0855	0.0670
7)	Conducted Heat Input (watts)	1198	1266	1280

(* 2, 3, 4 and 5 are calculated assuming matched load as described in the equations on page 12)

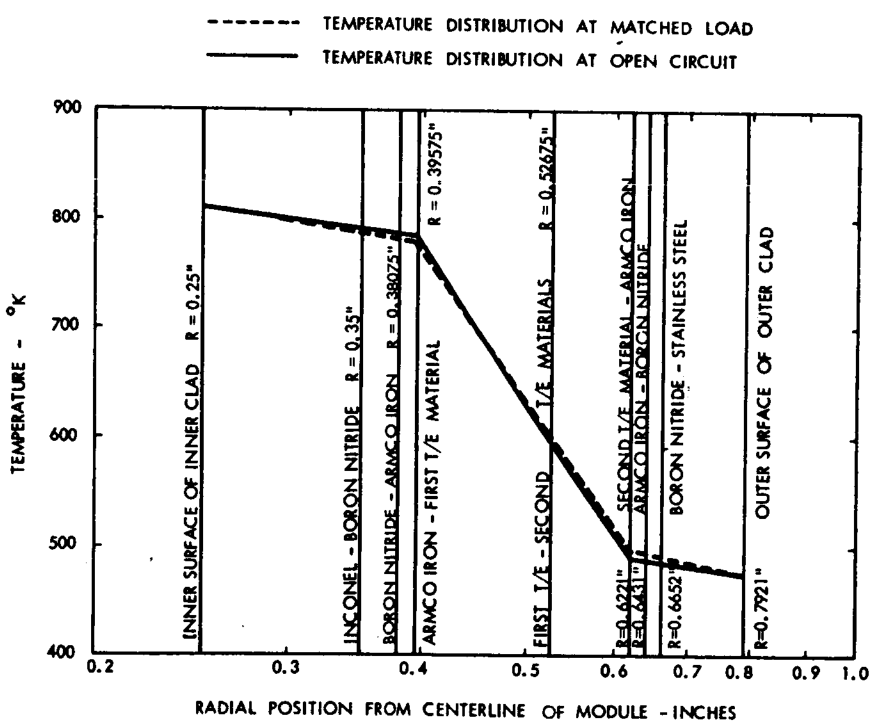

Figure 10. Calculated Temperature Distribution for Both Open Circuit and Matched Load Conditions

Plots of several significant parameters are given in Figures 11 through 15 as a function of module mean temperature, i.e. $(\bar{T}_H + \bar{T}_C) / 2$, where $\bar{T}_H$ and $\bar{T}_C$ are the mean hot and cold clad temperatures, respectively. The theoretical curves which were calculated using the average hot and cold clad temperatures during the startup, are presented for comparison.

Some of the discontinuities of the data points can be directly related to discontinuities in the theoretical curves. Such "steps" are the result of perturbations in the operating conditions. As an example, the large spike near the beginning of the startup corresponds to the point at which the cooling fan was turned on. Other sudden changes in the test data, not reflected in the theoretical curves, may be related to internal changes.

With the exception of the early part of the internal resistance plot, shown in Figure 12, the general form of the data points closely follows the theoretical curves on all the plots. The fact that the data points are uniformly below the theoretical curves indicates either a consistently poor interface condition along the axial length of the module, intercouple shorting, or a discrepancy between the values used for the theoretical calculations and the actual properties of the various materials.

As shown on the internal resistance plot of Figure 12, a rather rapid decrease was measured during the early part of the startup. Above the average temperature of about 200°C, the resistance runs essentially parallel to the theoretical curve.

LIFE TEST

Following initial warmup, the module was seasoned at conditions of 1280 ± 20 watts input, an average cold clad temperature of 200°C, and average hot clad temperature of 538°C. After 518 hours at these conditions, a thermal cycle to room temperature and return to seasoning conditions was performed. After the shutdown - startup cycle, the module was held at these seasoning conditions for an additional 70 hours to evaluate the effect of this cycle on module output. No observable effect was noted; module efficiency and output remained at the same level as that immediately prior to this cycle.

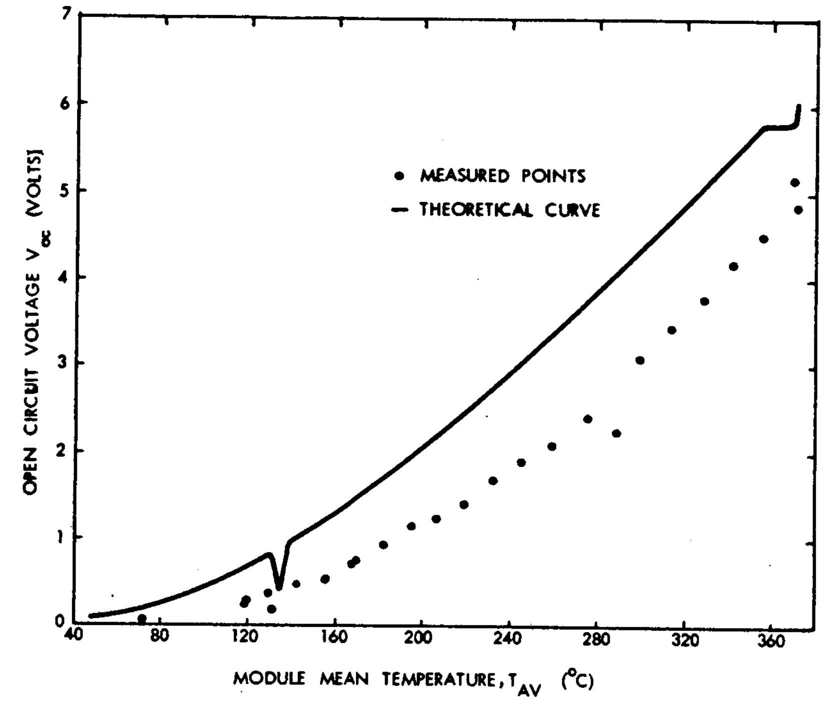

Figure 11. Open Circuit Voltage Versus Module Mean Temperature

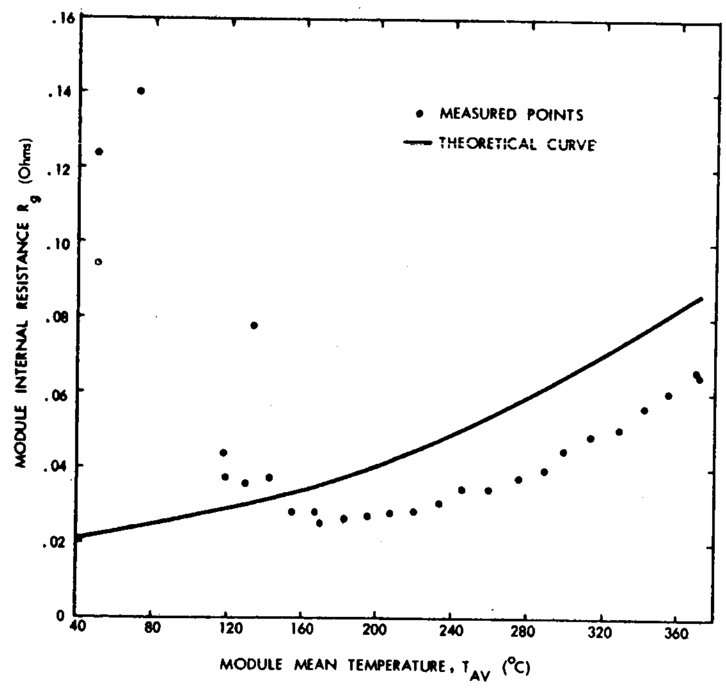

Figure 12. Module Internal Resistance Versus Module Mean Temperature

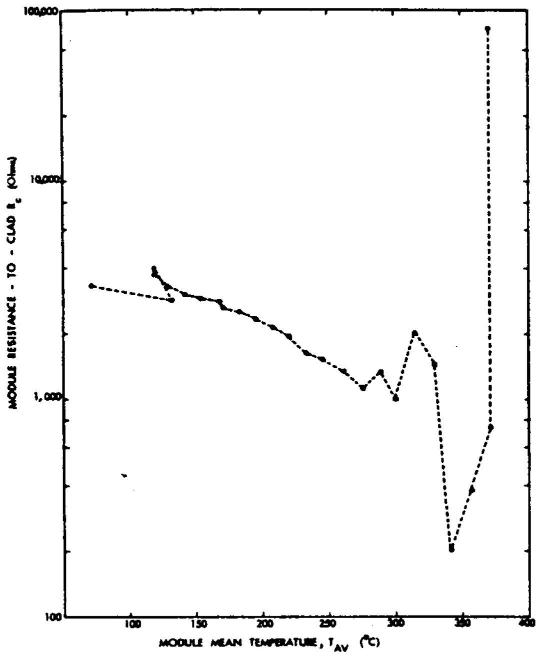

Figure 13. Module Resistance-to-Clad Versus Module Mean Temperature

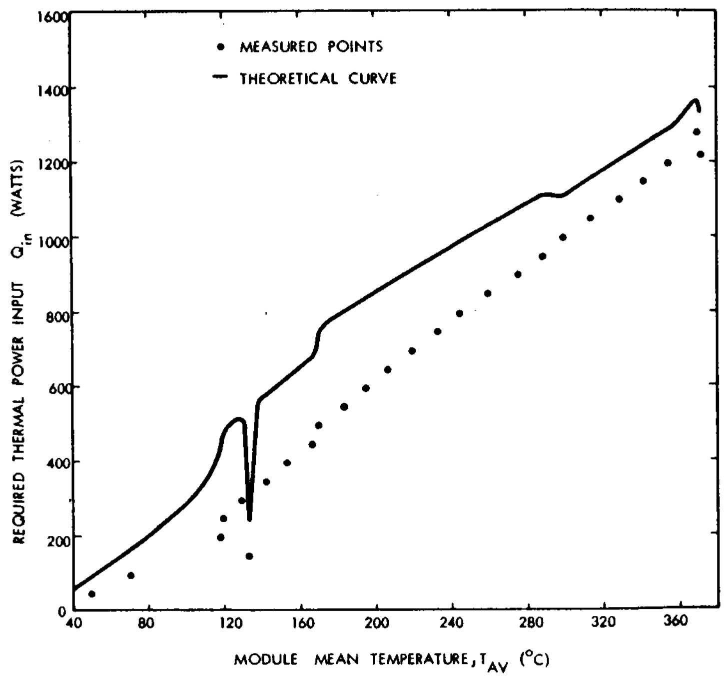

Figure 14. Required Thermal Power Input Versus Module Mean Temperature

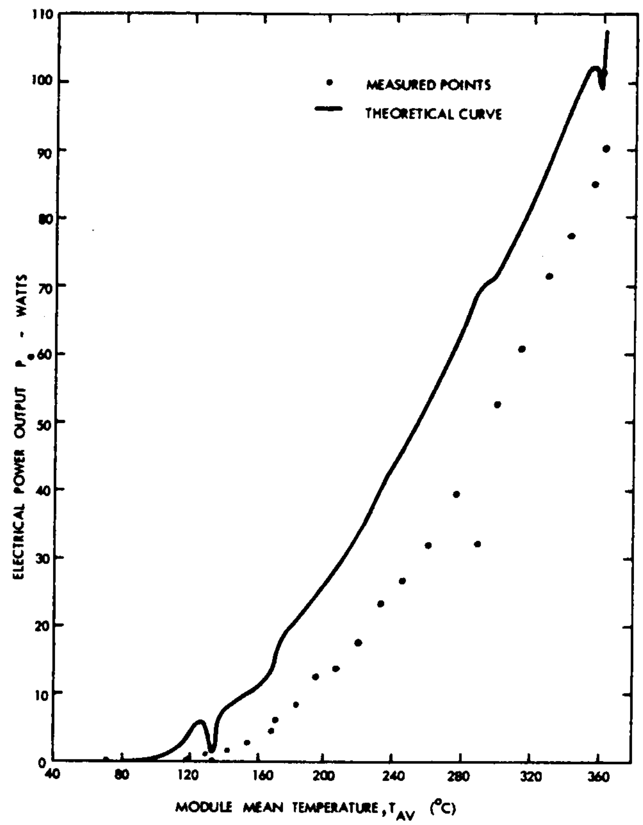

Figure 15. Electrical Power Input Versus Mean Temperature

For the first 800 hours of testing, the module was tested under open circuit conditions. This was done, first of all, to facilitate analysis, since under such conditions the thermoelectric and thermal effects can be treated separately. Secondly, because there is no current drawn from a device at open circuit (infinite load) conditions, the Peltier heat is zero (as are the Joule and Thompson heats), and thus the heater can be operated at a considerably lower power density (~ 30 percent). Under these conditions all other parameters of interest can be calculated to an accuracy sufficient for engineering purposes by the equations given earlier.

Using the average hot and cold clad temperatures for the first point of the life test, a comparison calculation was made to predict the operation of the module at matched load from open circuit parameters. This comparison is presented in Table 2, along with the actual data taken at the beginning of life testing. The difference between the calculated temperature distributions for the open circuit and matched load operations is shown in Figure 10.

As can be seen from Figures 16 through 20 and Table 2, the module started at initial values somewhat better than the predicted values. At about 375 hours, the efficiency and power output leveled off at about 4.9 percent and 80 watts, respectively. The thermal cycle at 518 hours had no measurable effect on the power output. However, the open circuit voltage and internal resistance continued to show the slowly increasing trends that had been exhibited before the cycle.

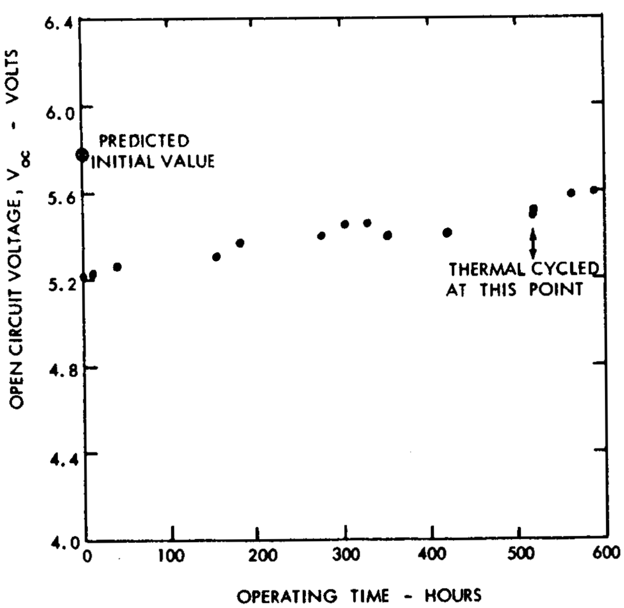

Figure 16. Open Circuit Voltage Versus Operating Time

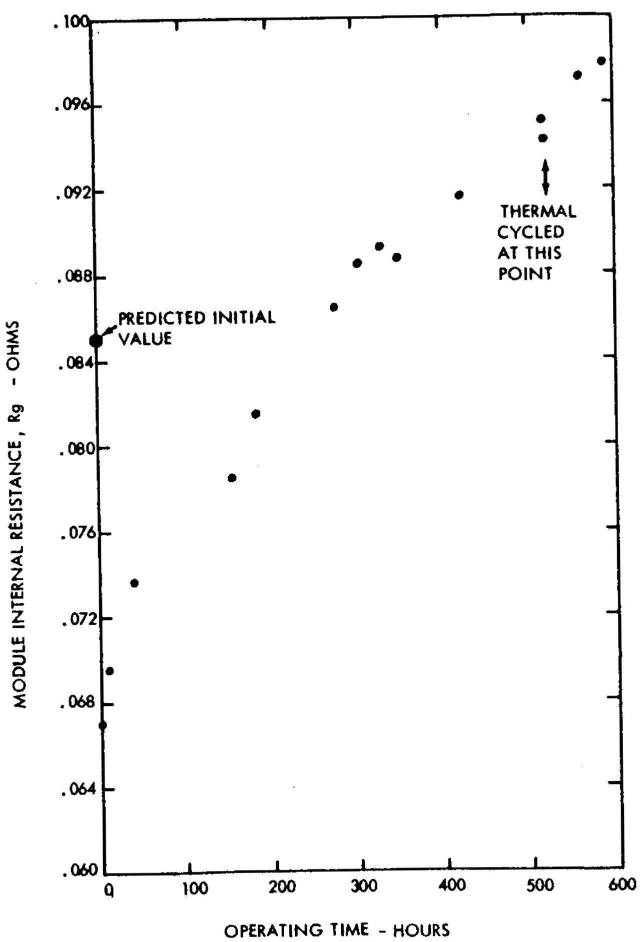

Figure 17. Module Internal Resistance Versus Operating Time

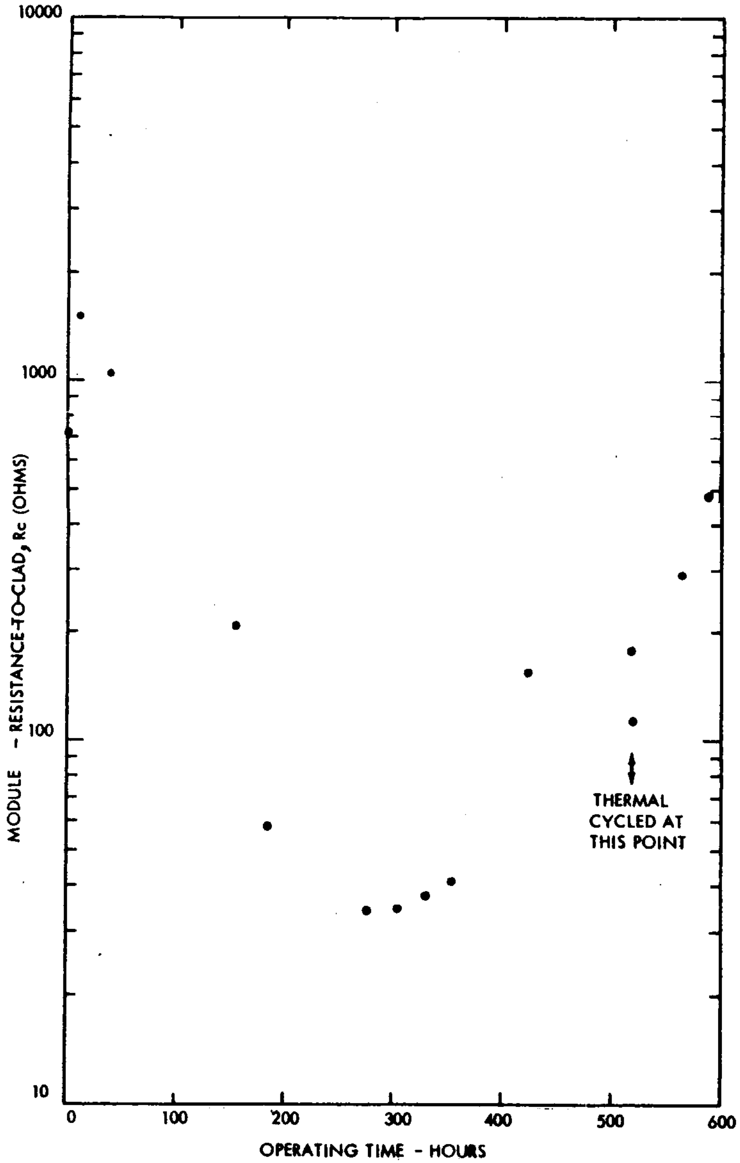

Figure 18. Module Resistance-to-Clad Versus Operating Time

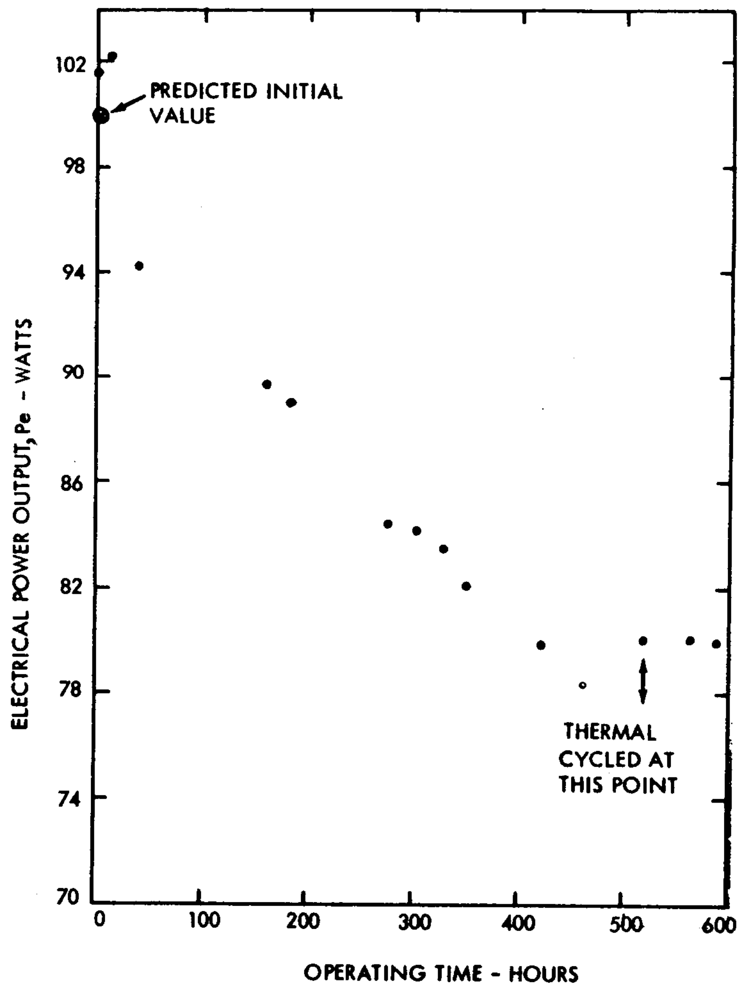

Figure 19. Electrical Power Output Versus Operating Time

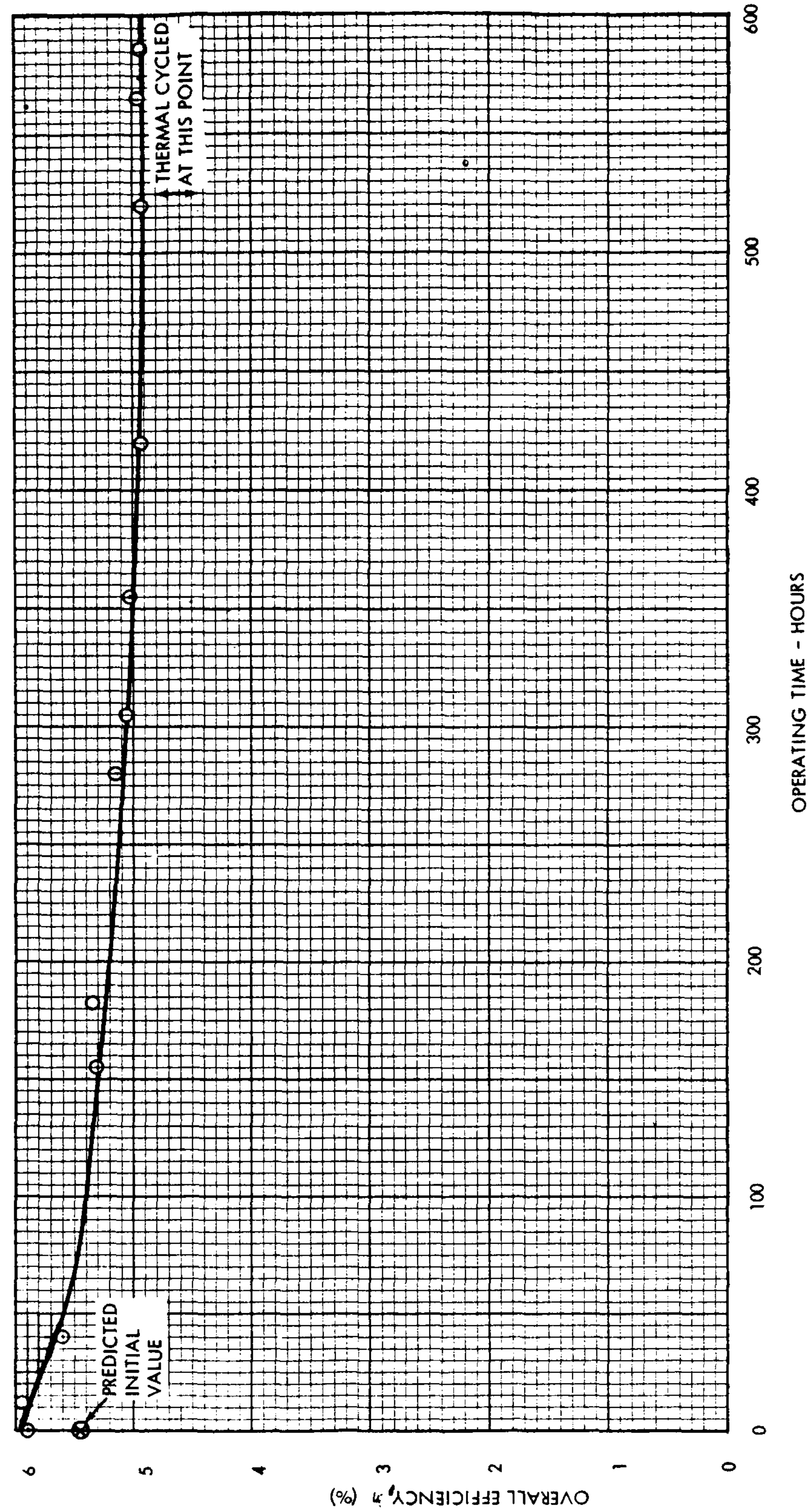

Figure 20. Overall Efficiency Versus Operating Time

THERMAL CYCLE

After 518 hours of testing, a thermal cycle to room temperature and back to the seasoning test conditions was performed. The module was cooled down in approximately 6 hours, left overnight at room temperature, and heated up in approximately the same length of time the next day. This cycle was performed to evaluate the effects of thermal cycling on performance and to see if there were consistent points of sudden change which would indicate closing or opening of interface gaps within the module. As can be seen in Figures 21 through 25, with the exception of the internal resistance and circuit to clad resistance, the cooldown and heatup curves are quite smooth and closely follow the theoretical curve.

Figure 22 shows that the internal resistance fluctuated considerably during both the cooling and heating processes. Such behavior is probably due to localized contact problems. This is also reflected in the resistance-to-clad measurements shown in Figure 23 for the thermal cycle. That the poor contacts are localized is further borne out by the relatively smooth plot for open circuit voltage shown on Figure 21.

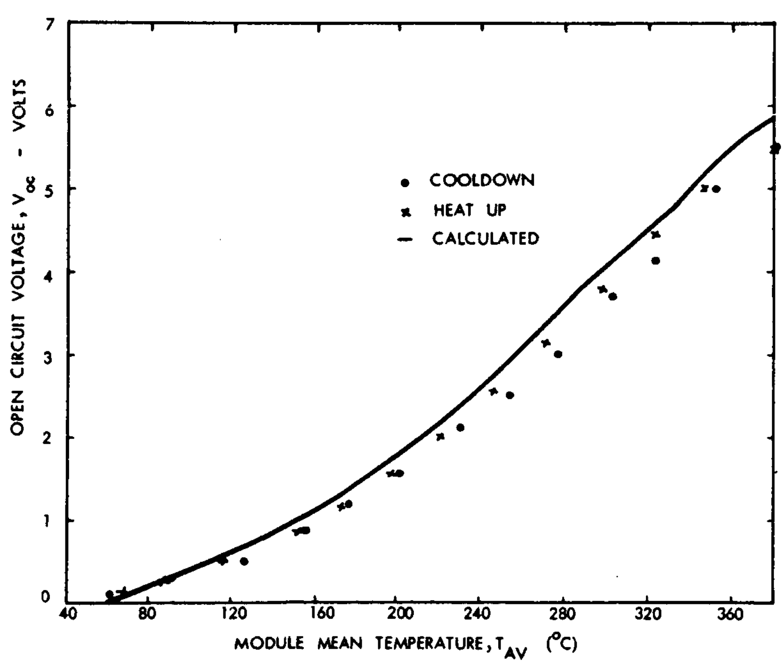

Figure 21. Open Circuit Voltage Versus Module Mean Temperature

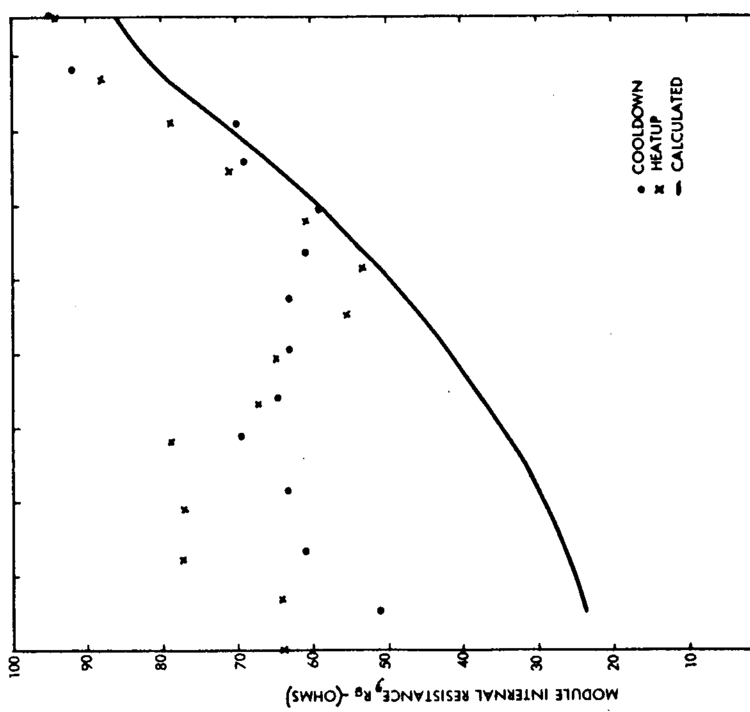

Figure 22. Module Internal Resistance Versus Module Mean Temperature

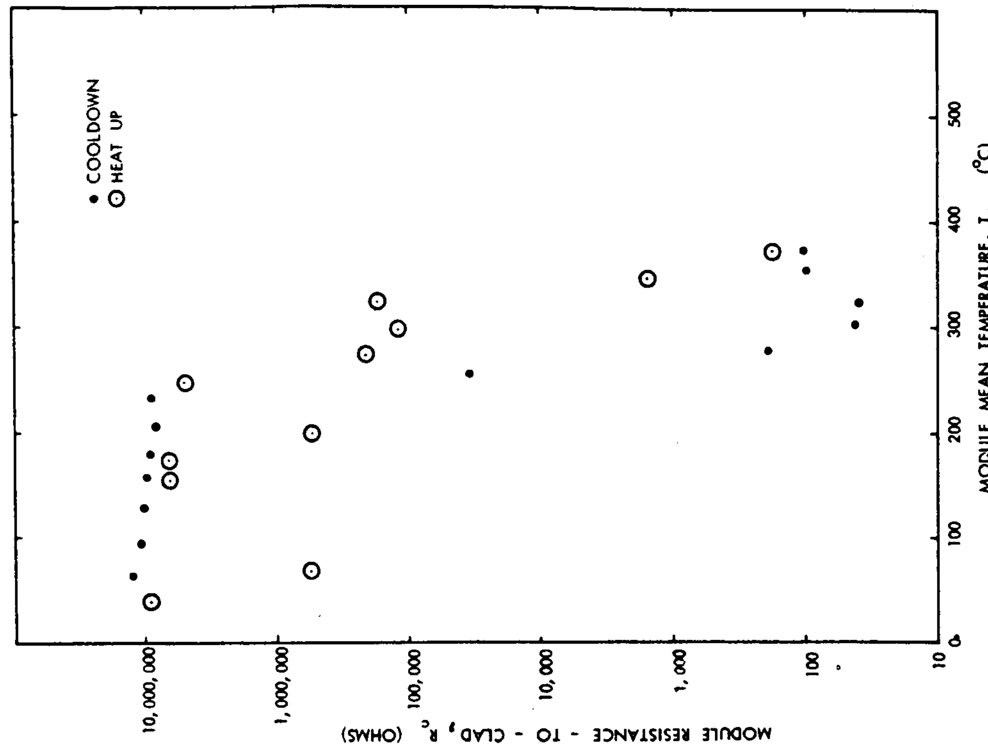

Figure 23. Module Resistance-to-Clad Versus Module Mean Temperature

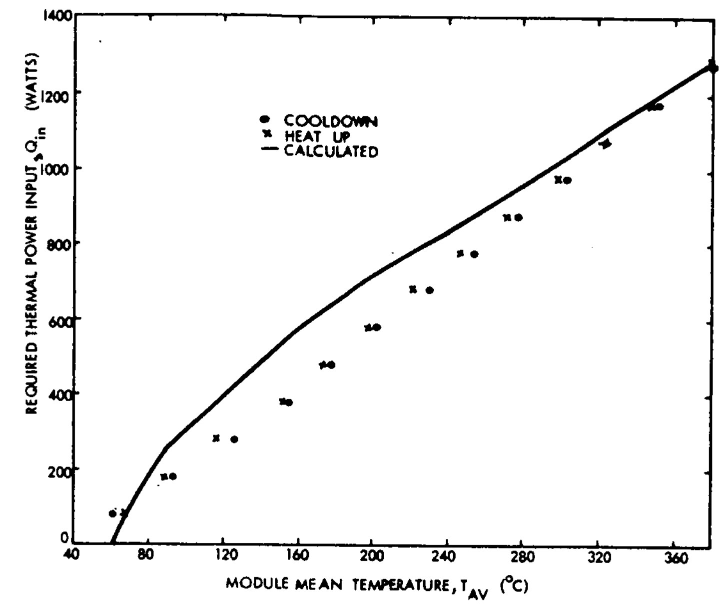

Figure 24. Required Thermal Power Input Versus Module Mean Temperature

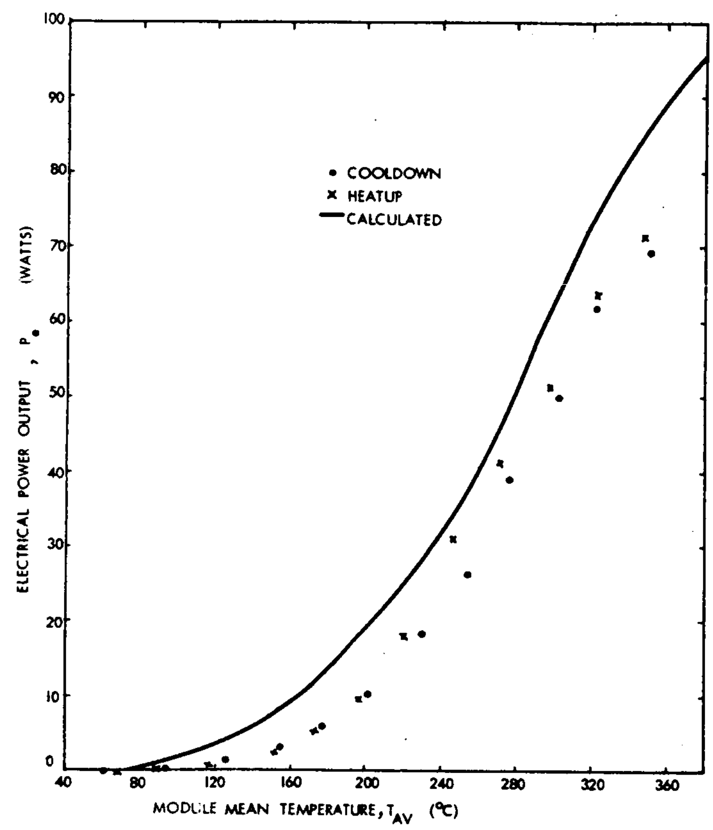

Figure 25. Electrical Power Input Versus Module Mean Temperature

Although the resistances varied markedly during changes in test conditions, the values before and after testing and at the end points of the initial warmup and thermal cycle were quite close. A comparison of circuit resistance and resistance-to-clad is presented in Table 3 for various points during the testing history.

TABLE 3

MEASURED RESISTANCE VALUES AT SELECTED POINTS IN TESTING HISTORY

Resistance Measured at the Following Points in Module History	Internal Resistance (ohms)	Average Temperature °C	Resistance-to-Clad (ohms)
Beginning of Start-Up	.127	Room Temperature	3300
First Point of Life Test	.067	370°	728
Before Thermal Cycle	.095	372°	114
At Room Temperature During Cycle	.064	Room Temperature	8.4×10^6
After Thermal Cycle	.094	371°	482
After Variations of $\bar{T}_C$	.069	286°	1350
After Variations of Q_{in}	.089	340°	504
After Being Removed from Test	.099	Room Temperature	4.5×10^8

OTHER HIGH TEMPERATURE TESTS

In order to determine the optimum operating conditions for the JPL module, the following performance test was conducted after the seasoning period. While holding the input power constant at 1280 watts, the cold clad temperature was decreased in 10°C intervals, allowed to stabilize at each position, and a data point taken. This testing was accomplished under open circuit conditions. The power output was calculated at each point and a rather broad maximum of power output was found at an average temperature of 340°C; $\frac{\bar{T}_H + \bar{T}_C}{2}$. For the desired hot side temperature of 538°C, at which such life testing of similar modules has been conducted, a cold side temperature of 140°C was required to achieve an average temperature of 340°C. Accordingly, while the cold side temperature was maintained at 140°C, the hot clad temperature was increased to 538°C, thereby achieving an average temperature of 340°C. At this point, the calculated power output was 110.6 watts and the calculated overall efficiency was 5.54 percent. The module was maintained under these conditions for approximately 170 hours and the calculated power and efficiency were very stable during this period.

After 800 hours of operation the module was coupled to a matched load and the thermal power input increased to compensate for the Peltier effect. At the resulting conditions of $\bar{T}_H = 538°C$, $\bar{T}_C = 140°C$, and $Q_{in} = 1930$ watts, the measured power output and efficiency were 100.6 watts and 5.21 percent respectively.

The module was operated at these matched load conditions for about 300 hours and the measured power and the efficiency continued stable during this period. Figure 26 shows the post-seasoning module performance.

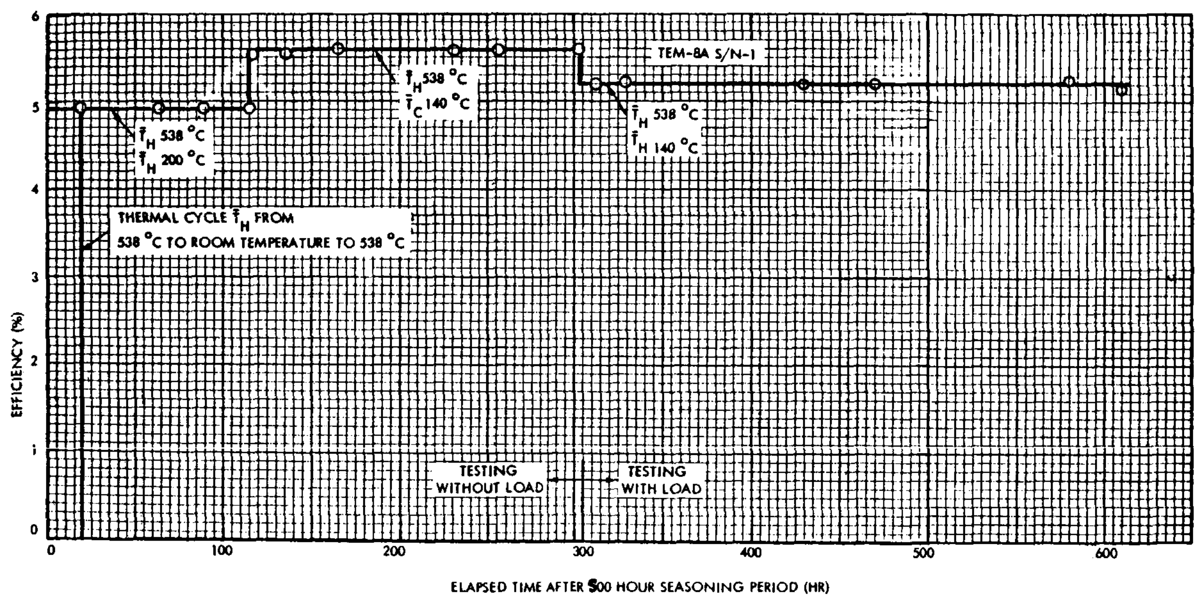

Figure 26. Post Seasoning Module Performance Overall Efficiency vs Operating Time

At this point a short circuit was applied to the module and a peak current of 51 amperes was recorded. The module was then shut down at the rate of 50 watts every 10 minutes. After cooling to room temperature, the internal resistance was measured using the Keithley model 503 Milliohmmeter and found to be 0.099 ohms. Using a General Megohmmeter on the 50 volt range, the resistance-to-clad was found to be 450×10^6 ohms.